Spectroscopic identification of DENIS-selected brown dwarf candidates in the Upper Scorpius OB association[1]

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ABSTRACT

We present low-resolution (R=900) optical (576.1–1,051.1 nm) spectroscopic observations of 40 candidate very low-mass members in the Upper Scorpius OB association. These objects were selected using the I, J and K photometry available in the DENIS database. We have derived spectral types and we have measured Hα and NaI doublet (at 818.3 and 819.5 nm) equivalent widths. We assess the youth of the objects by comparing them to their older counterparts of similar spectral type in the Pleiades cluster and the field. Our analysis indicates that 28 of our targets are young very low-mass objects, and thus they are strong candidate members of the OB association. The other 12 DENIS sources are foreground M dwarfs or background red giants. Our sample of spectroscopic candidate members includes 18 objects with spectral types in the range M6.5 and M9, which are likely young brown dwarfs. We classify these candidates as accreting/non accreting using the scheme proposed by Barrado y Navascués & Martín (2003). We find 5 substellar-mass candidate cluster members that are still undergoing mass accretion, indicating that the timescale for accretion onto brown dwarfs can be as long as 5 Myr in some cases.

Subject headings: open clusters and associations: UpperSco – Stars: low mass, brown dwarfs, pre-main-sequence, chromospheres

1. Introduction

The census of very low-mass (VLM) stars and brown dwarfs (BDs) is very incomplete, even in the immediate solar neighborhood, and in the nearest open clusters, star-forming regions and OB associations. Considerable progress has been achieved in the last few years, leading to the identification of hundreds of VLM stars and BDs and to the development of two new spectral classes, namely L and T, for ultracool dwarfs (Martín et al. 1997; Kirkpatrick et al. 1999; Jones & Steele 2001; Burgasser et al. 2002; Geballe et al. 2002). This huge observational effort has proved that VLM stars and BDs constitute a numerous population in the galactic disk. They are being incorporated in our current paradigm of star and planet formation (Boss 2002; Bate et al. 2002; Delgado-Donate et al. 2003; Kroupa et al. 2001, 2003; Sterzik & Durisen 2002) and stellar evolution (D'Antona & Mazzitelli 1994; Baraffe et al. 1998, 2002; Wuchterl & Tscharnuter 2003).

One of the most successful methods to identify VLM objects has been to obtain deep enough multicolor imaging of the classical young associations and clusters in the solar vicinity, and follow-up spectroscopy of the candidates that occupy the

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expected position of VLM members in the color-magnitude diagram. In the Pleiades open cluster, where the BD population is well studied, the success rate of imaging plus low-resolution spectroscopic characterization is about 90% (Mart´ in et al. 1996, 2000; Moraux et al. 2001). In younger regions, the success rate could be even higher because it is easier to apply gravity sensitive spectroscopic indicators due to the lower surface gravity of younger VLM objects.

Upper Scorpius (hereafter USco for brevity) is the youngest subgroup (age∼5 Myr, de Geus et al. 1989) of the nearest OB association (Scorpius-Centaurus). The average distance to the association is 145 pc, but there is a large scatter in the Hipparcos parallaxes of individual members (de Geus et al. 1989). The low-mass stellar population of USco has been studied by Walter et al. (1994), Martín (1998), and Preibisch et al. (1998, 2001). The VLM population was first revealed by Ardila et al. (2000).

In this paper we present the spectroscopic characterization of 36 new candidate VLM members in the USco association. 3 of our targets (cross identifications are given in Table 1) were already found by Ardila et al. (2000). One of them, namely DENIS161007.5-181056.4, was already included in the survey of Preibisch et al. (2001). Our candidates were identified in the database of the DEep Near-Infrared Survey (DENIS) using I, J and K photometry (Epchtein et al. 1994). DENIS has already been mined to identify nearby field VLM stars and BDs (Delfosse et al. 1997, 1999; Phan-Bao et al. 2001, 2003). A preliminary report of the results of this survey can be found in Delfosse et al. (2003). A paper dedicated to the BD initial mass function (IMF) in a rich star formation region -such as an OB association- and the distribution of VLM USco members, will be forthcoming (Delfosse et al. in prep). The comparison of the BD IMF for star formation regions with different densities (from OB associations to T Tauri associations) will be a stepping stone to understand BD formation. The present paper is focused on the spectroscopic follow up and identification of the DENIS BD candidates in the USco association.

In section 2, we present the observations and data reductions. Section 3 deals with the spectroscopic measurements and data analysis. In section 4 we assess the membership of the candidates in USco. Section 5 consists of a discussion of the properties of the objects.

2. Sample selection, observations and data reduction

Our sample of 40 VLM candidate members in USco was selected from the DENIS database. The DENIS 100% completeness limit is I=18.0, which for the NextGen models (Baraffe et al. 1998) translates into a 20 $M_{\rm Jup}$ brown dwarfs at the age ($\sim$ 5Myr) and average distance ($\sim$ 145pc) of the association. Our search was made in 60 square degrees of the association, centered at the galactic coordinate $l = 347^o$, $b = 25^o$. The already known members of the association are mainly located in a band 2 mag higher than the main-sequence in the H-R diagram. Preibisch et al. (2001) find that only ∼10% of USco stars are outside such band. In Figure 1 we show the color-magnitude diagram for our DENIS survey in USco. The NextGen 5Myr theoreticaly isochrones for distances of 120 pc and 200 pc mark the band of expected location for the association members. Our search is focused on the red part of this band. After artifact rejection, 104 objects were retained as candidate with color redder than $I - J = 2.3$. Nine of them were already detected by Ardila et al. (2000), and one was reported by Preibisch et al. (2001), all the other are new.

The candidates of Ardila et al. (2000) detected in the 60 square degrees of our DENIS survey are marked in Figure 1. 15% of them are outside the band. Our search is not complete because it lacks over-luminous or sub-luminous members (e.g. binary or obscured objects), but we are available to detect 80-90% of Ardila's candidate members. We refer the reader to Delfosse et al. (in preparation) for a detailed analysis, dedicated to determine luminosity and mass functions of the brown dwarf sequence in the association.

Optical spectroscopy was obtained for 40 objects out of our 104 candidates. The spectroscopic target list is constituted by the redder candidates (all except two for $I - J > 3.0$) and by candidate regularly spaced out on the rest of the sequence to estimate the association membership fractions of our candidates in function of their localization in the color-magnitude diagram. The spectroscopic observations were obtained in service mode at the

ESO NTT telescope using the EMMI spectrograph on the nights of 13-16 June 2002 and 7-8 August 2002. Exposure times for each target are given in Table 1. The CCD frames were trimmed, dark subtracted, and flat fielded before extracting one dimensional spectra. The spectra were wavelength calibrated using an arc lamp spectrum, and flux calibrated using a standard star spectrum. All reduction operations were carried out in the IRAF environment. The wavelength coverage was 576.1–1,051.1 nm at a dispersion of 0.177 nm/pix and a resolving power of R=900. In Figure 2 we display a representative subset of our final spectra. The main spectral features have been identified following Kirkpatrick et al. (1991) and Martín et al. (1996).

3. Analysis

In Table 2 we provide the measurements obtained from the spectra of our targets. We have measured W(Hα) and W(NaI) at 818.3 and 919.0 nm using the IRAF task splot. The pseudocontinuum was placed by visual inspection of the spectra. The measurement errors are dominated by uncertainties in the location of the pseudocontinuum. Spectroscopic indices of the strength of TiO and VO bands, and the slope of the pseudocontinuum (PC3), were also evaluated using the definitions in Martín et al. (1999). We used the PC3-spectral type calibration provided by these authors to obtain spectral types for our objects. We checked that the TiO and VO values were consistent with the spectral type determined from the PC3 index. We do not find evidence for any significant reddening in our sample. We estimate that Av<1 for most of our objects. Ardila et al. (2000) found only two objects with Av>1 among 23 VLM USco candidates. Our dataset is not as sensitive to reddening as that of Ardila et al. because we lack the $R-I$ color.

3.1. Cluster membership assessment

We assess the membership of the candidates in USco on the basis of their location in the magnitude-spectral type and W(NaI)-spectral type diagrams.

In Figure 3 we plot our targets in a spectral type - magnitude diagram. Note that six objects are located outside the cluster sequence. They have spectral types that are too early for their I magnitude. We consider them as likely non-members. Five of them do not present Hα in emission. They are probably background red giants. We discard them from further analysis because they are not interesting for the purposes of this paper.

The NaI doublet at 818.3 and 819.5 nm is a well known gravity indicator for late-M spectral types (Kirkpartrick et al. 1991; Martín et al. 1996; Briceño et al. 1998). It becomes weaker for decreasing surface gravity. In Figure 4 we plot our W(NaI) values versus spectral type and we compare with the field dwarfs measured by Martín et al. (1996). VLM USco candidates that W(NaI) similar to those of field dwarfs are considered likely foreground cool dwarfs. The USco members are expected to be young, and hence they should have larger radius, lower surface gravity and weaker W(NaI) than their field counterparts of the same spectral type. The USco candidates with W(NaI) weaker than the field objects are retained as likely cluster members.

Hα emission is normally seen among young VLM stars and BDs. It can originate from chromospheric activity or from disk accretion onto the central object. We expect that the young USco VLM members have Hα emission because they are chromospherically active and may still have some leftover accretion activity. We do not use Hα emission as a membership criterion, but we note that all the 28 likely members listed in Table 2 clearly have Hα in emission.

3.2. Mass accretion

In order to identify classical T Tauri stars and substellar analogs using only low-resolution optical spectroscopy, Barrado y Navascués & Martín (2003) have proposed a W(Hα) boundary line that depends on the spectral type, and it is based on the chromospheric saturation limit at Log $\{L(H\alpha)/L(bol)\}=-3.3$, observed in young open clusters. Objects with W(Hα) larger than the boundary are likely accretors. In Figure 5 we display the W(Hα) of our USco objects as a function of spectral type. We also show the Barrado y Navascués & Martín boundary line. Six objects from our sample, and one from Ardila et al.'s sample, are located above the line. Hence, they are likely accretors. Five of the accretors have spectral types later than M6, so they are probably

substellar[4].

Barrado y Navascués & Martín (2003) have combined our results with the literature to estimate a frequency of accretors of 14.4±5.7% for the spectral type range K3-M5.5, while for the spectral type range M5.5-M9 the frequency is 16.3±6.2% . Hence, there is no evidence for a strong dependence of the number of accreting objects with primary mass in the USco low-mass population. Other studies based on infrared color excesses have reached similar conclusions (Haisch et al. 2001; Muench et al. 2001; Natta et al. 2002; Jayawardhana et al. 2003; Liu et al. 2003). Our sample of USco likely substellar accretors deserves further follow-up observations to determine their spectral energy distribution and mass accretion rates.

4. Discussion

In this paper we have presented new evidence for a numerous VLM population in the USco OB association. We refer the reader to Delfosse et al. (in preparation) for a discussion of the VLM luminosity and mass functions in USco.

We have identified 28 objects with spectral types in the range M5.5-M9 as likely VLM members on the basis of their spectroscopic characteristics. They are located in the cluster sequence in the magnitude-spectral type diagram, they have relatively weak NaI lines, and they show Hα in emission. Five of them meet the Barrado y Navascués & Martín criterion for substellar classical T Tauri analogs. Since these accreting BDs are likely members of the OB association, their age is 5 Myr, implying that accretion onto BDs can last a significant amount of time.

Together with the VLM candidates presented by Ardila et al. (2000), and the follow-up spectroscopic observations of 12 of them (none of which overlap with our sample) by Mohanty et al. (2003), our study brings the number of spectroscopically identified USco VLM candidate members to 40. The membership of the objects needs to be confirmed with follow-up studies of proper motion and radial velocities. This is now a significant sample for systematic studies of the properties of young VLM objects, such as accretion, binarity and rotation. Due to its relative proximity, young age, and richness, USco is one of the most important regions for studies of substellar-mass formation and evolution. To compare the IMF in such a rich star formation region with the one of less dense regions (as the T Tauri associations) will be very useful to constrain the sensitivity of BD formation to environmental conditions.

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Table 1: USco DENIS candidate members

Name	I	J	K	t_{exp} (s)	Notes
DENIS-PJ151450.1-225435.3	17.08±0.09	13.96±0.08	12.86±0.17	2x510	
DENIS-PJ151713.7-200238.9	15.40±0.10	13.07±0.07	12.07±0.10	300	
DENIS-PJ153338.7-201856.0	16.70±0.09	14.13±0.10	13.03±0.12	2x300	
DENIS-PJ155504.9-204258.3	17.90±0.18	14.75±0.15	13.48±0.22	2x600	
DENIS-PJ155556.0-204518.5	16.20±0.07	13.43±0.10	11.94±0.11	2x300	
DENIS-PJ155601.0-233808.1	16.32±0.09	13.96±0.11	12.85±0.14	2x300	UScoCTIO113
DENIS-PJ155605.0-210646.4	16.85±0.09	14.11±0.12	12.74±0.13	2x450	
DENIS-PJ160019.5-225628.4	17.45±0.12	14.67±0.14	13.41±0.18	2x510	UScoCTIO131
DENIS-PJ160334.7-182930.4	14.84±0.07	12.47±0.07	11.43±0.09	300	
DENIS-PJ160440.8-193652.8	16.09±0.06	13.52±0.10	12.40±0.11	2x300	
DENIS-PJ160455.8-230743.8	16.45±0.08	13.88±0.11	12.71±0.13	2x300	UScoCTIO117
DENIS-PJ160514.0-240652.6	15.22±0.05	12.78±0.08	11.94±0.10	300	
DENIS-PJ160603.9-205644.6	16.38±0.09	13.54±0.08	12.37±0.10	2x300	
DENIS-PJ160809.0-272748.0	16.46±0.08	14.11±0.13	13.30±0.17	2x300	
DENIS-PJ160951.1-272242.2	15.68±0.06	13.33±0.09	12.33±0.11	2x300	
DENIS-PJ160958.5-234518.6	15.04±0.04	12.66±0.08	11.49±0.08	300	
DENIS-PJ161005.4-191936.0	17.16±0.12	14.21±0.12	12.80±0.14	2x500	
DENIS-PJ161006.0-212744.6	18.11±0.20	14.74±0.15	13.59±0.22	2x600	
DENIS-PJ161007.5-181056.4	15.11±0.05	12.80±0.08	11.70±0.09	300	
DENIS-PJ161030.1-231516.7	17.04±0.11	14.37±0.13	13.19±0.17	2x450	
DENIS-PJ161050.0-221251.8	15.05±0.04	12.68±0.08	11.64±0.10	300	
DENIS-PJ161103.6-242642.9	17.80±0.16	14.68±0.15	13.34±0.17	2x600	
DENIS-PJ161420.6-274549.6	17.42±0.11	14.59±0.11	13.55±0.22	2x510	
DENIS-PJ161452.6-201713.2	18.56±0.20	15.33±0.15		3x900	
DENIS-PJ161624.0-240830.2	15.51±0.11	13.12±0.06	12.14±0.11	300	
DENIS-PJ161632.2-220520.2	16.06±0.12	13.71±0.08	12.66±0.13	2x300	
DENIS-PJ161758.1-265034.0	16.76±0.08	14.25±0.10	12.82±0.16	2x450	
DENIS-PJ161816.2-261908.1	14.60±0.03	12.20±0.07	10.90±0.06	300	
DENIS-PJ161820.5-260007.8	16.91±0.09	14.28±0.11	12.96±0.14	2x450	
DENIS-PJ161833.2-251750.4	15.03±0.04	12.51±0.07	11.22±0.06	300	
DENIS-PJ161840.8-220948.1	16.36±0.07	13.79±0.09	12.84±0.13	2x300	
DENIS-PJ161855.1-260035.2	18.09±0.18	15.06±0.14		2x600	
DENIS-PJ161903.4-234408.8	17.00±0.09	14.18±0.10	12.74±0.13	2x450	
DENIS-PJ161916.5-234722.9	17.98±0.15	14.83±0.13	13.70±0.22	2x450	
DENIS-PJ161926.4-241244.5	15.96±0.05	13.56±0.09	12.29±0.10	2x300	
DENIS-PJ161929.9-244047.1	17.32±0.10	14.21±0.10	12.86±0.13	2x510	
DENIS-PJ161939.8-214535.1	15.64±0.04	13.21±0.08	12.07±0.09	2x300	
DENIS-PJ162037.8-242757.8	17.56±0.13	14.57±0.12	13.08±0.16	2x510	
DENIS-PJ162041.5-242549.0	17.52±0.13	14.42±0.11	13.00±0.15	2x510	
DENIS-PJ162058.0-200846.1	17.67±0.14	14.23±0.11	11.98±0.10	2x510	

Table 2: Spectroscopic measurements and membership assessment

Name	W(Hα) (Å)	PC3	TiO	VO	W(NaI) (Å)	SpT	Member?
DENIS-PJ151450.1-225435.3	>-6.5	2.40±0.03	3.4	2.6	6.8±0.6	M9.5	No
DENIS-PJ151713.7-200238.9	-5±1	1.48±0.07	3.4	2.4	7.2±0.7	M6	No
DENIS-PJ153338.7-201856.0	-6±2	1.84±0.04	3.9	2.6	8.2±0.5	M8	No
DENIS-PJ155504.9-204258.3	-14±5	1.95±0.07	4.5	2.7	7.0±1.0	M8.5	No
DENIS-PJ155556.0-204518.5	-11±3	1.50±0.03	2.9	2.5	3.6±0.3	M6.5	Yes
DENIS-PJ155601.0-233808.1	-20±3	1.52±0.01	4.0	2.7	5.2±0.2	M6.5	Yes
DENIS-PJ155605.0-210646.4	-20±2	1.64±0.05	4.0	2.8	4.7±0.3	M7	Yes
DENIS-PJ160019.5-225628.4	-5±3	1.81±0.04	4.3	2.8	5.2±0.8	M8	Yes
DENIS-PJ160334.7-182930.4	-19±1	1.37±0.04	3.1	2.4	3.5±0.3	M5.5	Yes
DENIS-PJ160440.8-193652.8	-16±2	1.52±0.01	3.7	2.6	4.9±0.3	M6.5	Yes
DENIS-PJ160455.8-230743.8	-25±3	1.56±0.01	3.9	2.7	5.3±0.4	M6.5	Yes
DENIS-PJ160514.0-240652.6	-24±1	1.42±0.03	3.6	2.6	3.4±0.3	M6	Yes
DENIS-PJ160603.9-205644.6	-105±12	1.68±0.04	3.7	2.7	4.2±0.3	M7.5	Yes
DENIS-PJ160809.0-272748.0	-6±1	1.32±0.01	2.6	2.3	5.1±0.2	M5	No
DENIS-PJ160951.1-272242.2	-22±2	1.44±0.02	3.6	2.6	4.5±0.1	M6	Yes
DENIS-PJ160958.5-234518.6	-20±1	1.51±0.02	3.6	2.6	4.5±0.2	M6.5	Yes
DENIS-PJ161005.4-191936.0	-48±4	1.65±0.01	3.5	2.7	3.2±0.1	M7	Yes
DENIS-PJ161006.0-212744.6	-17±3	2.02±0.01	4.3	2.9	3.8±0.1	M8.5	Yes
DENIS-PJ161007.5-181056.4	-19±1	1.46±0.01	3.6	2.5	4.1±0.2	M6	Yes
DENIS-PJ161030.1-231516.7	-12±4	1.74±0.04	4.2	2.7	7.6±0.7	M7.5	No
DENIS-PJ161050.0-221251.8	-23±1	1.39±0.01	3.3	2.5	4.5±0.1	M5.5	Yes
DENIS-PJ161103.6-242642.9	-28±3	2.07±0.05	4.3	2.9	3.8±0.2	M9	Yes
DENIS-PJ161420.6-274549.6	-26±2	1.76±0.01	4.0	2.7	6.3±0.9	M7.5	No
DENIS-PJ161452.6-201713.2	-51±5	2.10±0.05	4.3	3.0	4.4±0.5	M9	Yes
DENIS-PJ161624.0-240830.2	-13±1	1.35±0.03	3.1	2.4	4.2±0.2	M5.5	Yes
DENIS-PJ161632.2-220520.2	-12±1	1.43±0.02	3.1	2.4	4.0±0.2	M6	Yes
DENIS-PJ161758.1-265034.0	>-3	1.51±0.04	2.4	2.3	3.5±0.3	M5	No
DENIS-PJ161816.2-261908.1	-9±1	1.38±0.03	2.6	2.4	1.4±0.1	M5.5	Yes
DENIS-PJ161820.5-260007.8	>-2	1.67±0.10	1.9	2.1	3.3±1.0	M3.5	No
DENIS-PJ161833.2-251750.4	-17±1	1.49±0.10	2.6	2.4	3.0±0.2	M6	Yes
DENIS-PJ161840.8-220948.1	-11±2	1.63±0.02	3.6	2.6	4.2±0.9	M7	Yes
DENIS-PJ161855.1-260035.2	>-1	1.30±0.02	2.4	2.2	3.3±1.0	M3	No
DENIS-PJ161903.4-234408.8	-15±6	1.57±0.01	2.9	2.5	3.5±0.2	M6.5	Yes
DENIS-PJ161916.5-234722.9	-125±10	1.89±1.12	2.7	2.5	2.0±0.4	M8	Yes
DENIS-PJ161926.4-241244.5	-14±1	1.46±0.01	3.1	2.5	3.6±0.2	M6	Yes
DENIS-PJ161929.9-244047.1	-65±15	1.80±0.02	3.9	2.7	3.6±0.2	M8	Yes
DENIS-PJ161939.8-214535.1	-61±7	1.60±0.03	3.5	2.4	5.2±0.8	M7	Yes
DENIS-PJ162037.8-242757.8	>-2	1.63±0.03	2.4	2.3	3.8±0.5	M4	No
DENIS-PJ162041.5-242549.0	-11±8	1.74±0.01	3.6	2.8	3.8±0.5	M7.5	Yes
DENIS-PJ162058.0-200846.1	>-3	1.91±0.05	1.8	2.0	3.8±0.5	M3	No

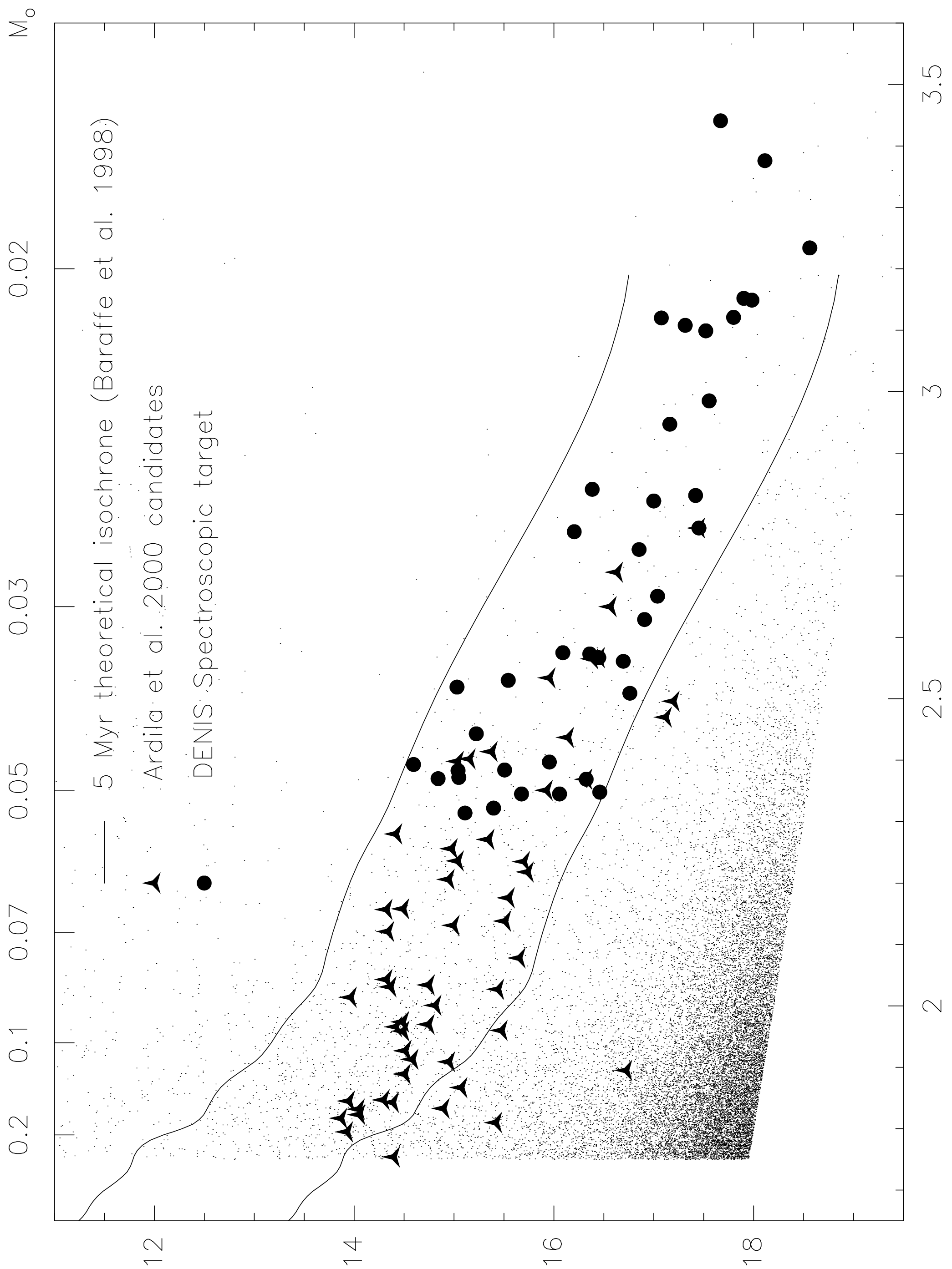

Fig. 1.— I vs $I-J$ color-magnitude diagram for our targets for spectroscopic follow-up detected by DENIS in 60 squares degrees of the Upper Scorpius OB association. The two solid lines delimit the area of candidate members, based on the Baraffe et al. 1998 theoretical isochrone for 5 Myr and distances of 120 pc and 200 pc. The dots are objects in the DENIS database (inluding artifacts), and the empty circles are DENIS spectroscopic targets discussed in the present paper. The triangles are brown dwarfs that were also previously identified by Ardila et al. (2000). The mass labels on the top axis are deduced from $I-J$ using the Baraffe et al. (1998) models.

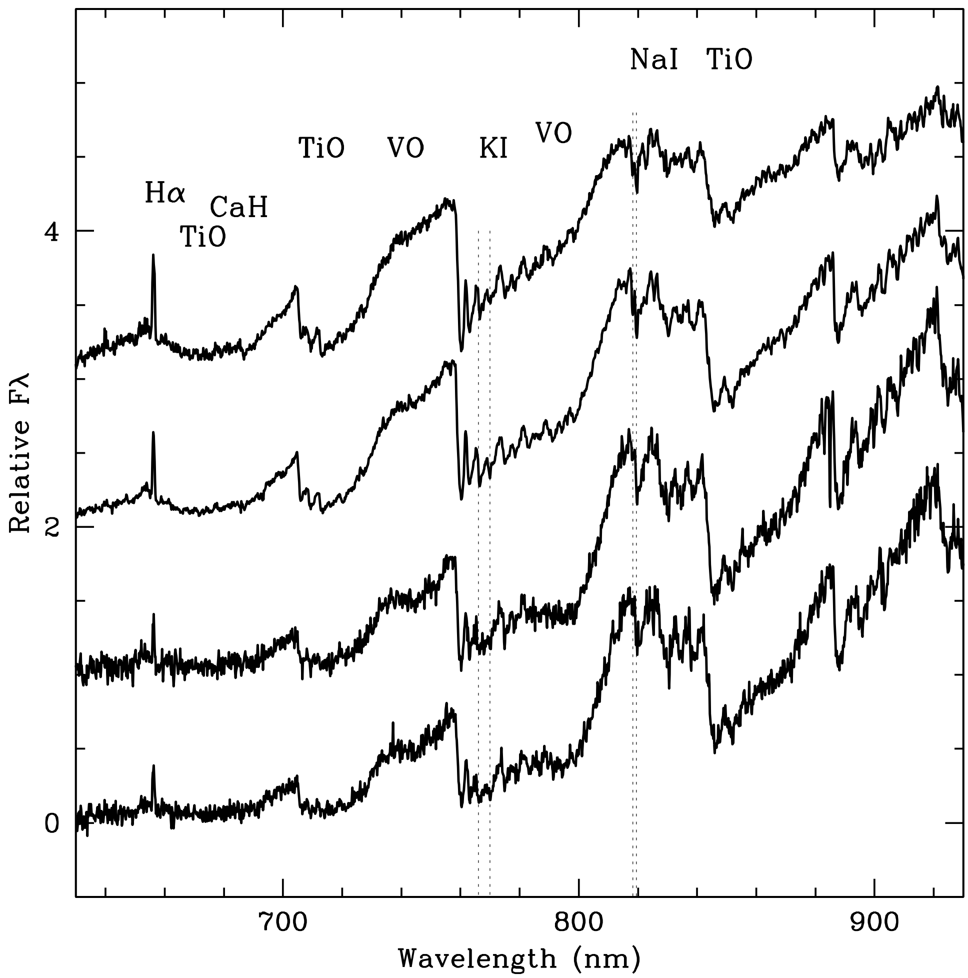

Fig. 2.— Final spectra for a representative subset of our targets. From top to bottom: DENIS-PJ160334.7-182930.4 (M5.5), DENIS-PJ160951.1-272242.2 (M6.5), DENIS-PJ161006.0-212744.6 (M8.5), and DENIS-PJ161103.6-242642.9 (M9).

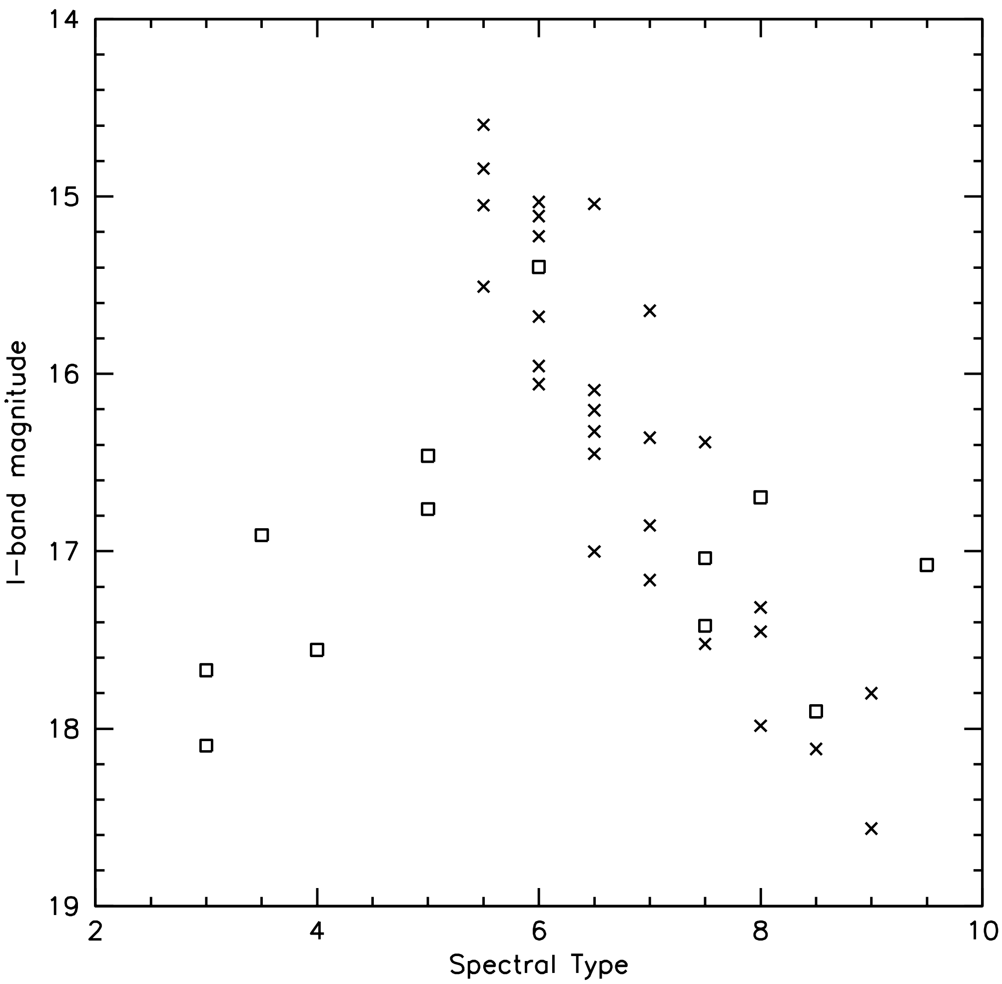

Fig. 3.— Spectral type - magnitude diagram for our program objects. Crosses denote likely USco members on the basis of their spectral type, Hα equivalent width and NaI equivalent width. Empty squares denote probable non-members.

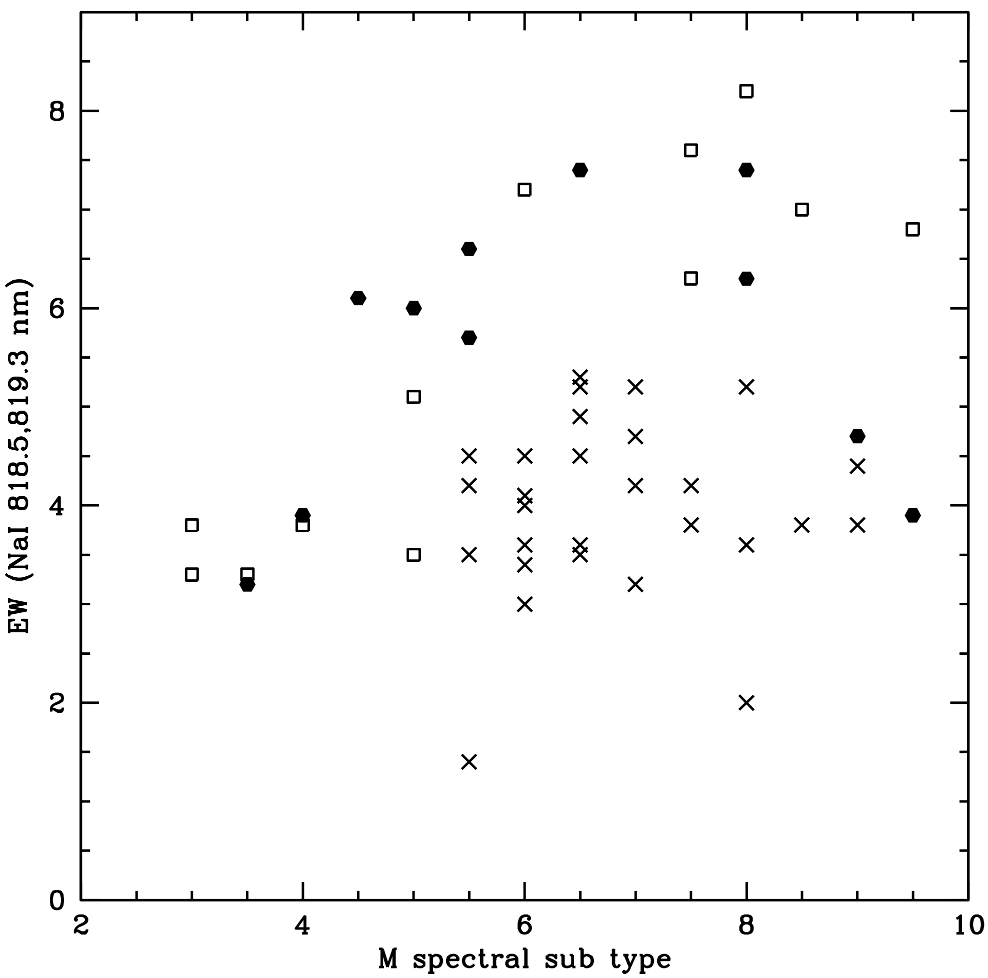

Fig. 4.— Spectral type - W(NaI) diagram for our program objects. Crosses denote likely USco members. Empty squares denote probable non-members. Filled hexagons represent field dwarfs from Martín et al. 1996.

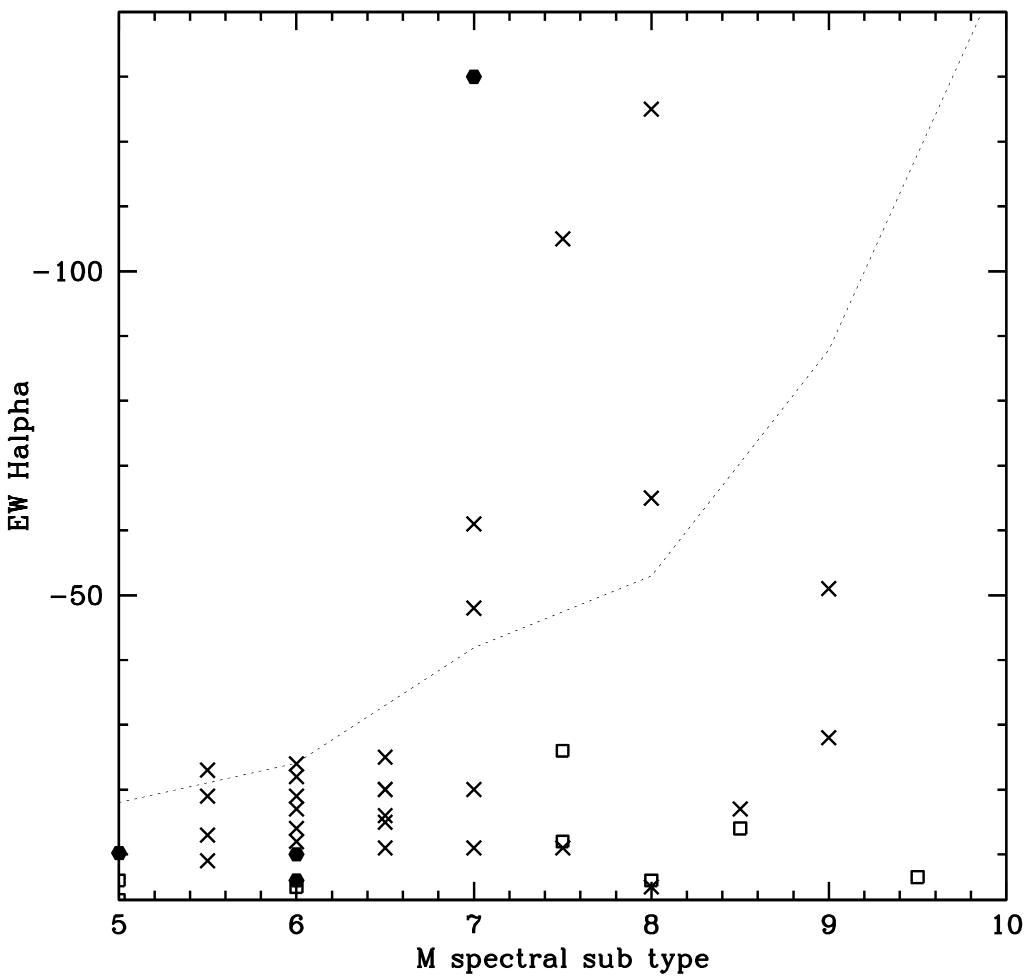

Fig. 5.— Spectral type - W(Hα) diagram for our program objects. Crosses denote likely USco members. Empty squares denote probable non-members. Filled hexagons represent USco candidates from Ardila et al. 2000. The dashed line marks the boundary between accreting and non-accreting objects according to the saturation criterion defined by Barrado y Navascués & Martín (2003).